DRAFT

PRECISION MECHANISMS FOR SPACE INTERFEROMETERS

A TUTORIAL

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# OUTLINE

1. MOTIVATION

20 ACTUATOR COMPONENTS

3. DESIGN EXAMPLES

4. TIPS FOR SPECIFYING ACTUATORS

1. MOTIVATION

- There is a strong correlation between the quantity and quality of science from space-born interferometers, and the number of moving parts on the spacecraft.

    - More baselines (and trolleys)= more star comparisons
    - Steerable mirrors enables better pointing accuracy, fainter targets
    - Articulated solar panel enables greater sky coverage.

- New NASA philosophy: "It's the price, stupid."

- Moving parts are expensive, and therefore not strongly compatible with this philosophy.

- To maximize salability, spaceborne interferometer designs must minimize actuator cost while maximizing science quality and quantity.

- Interferometer designers must have the knowledge to design a system with the simplest, most reliable, and least expensive actuators possible.
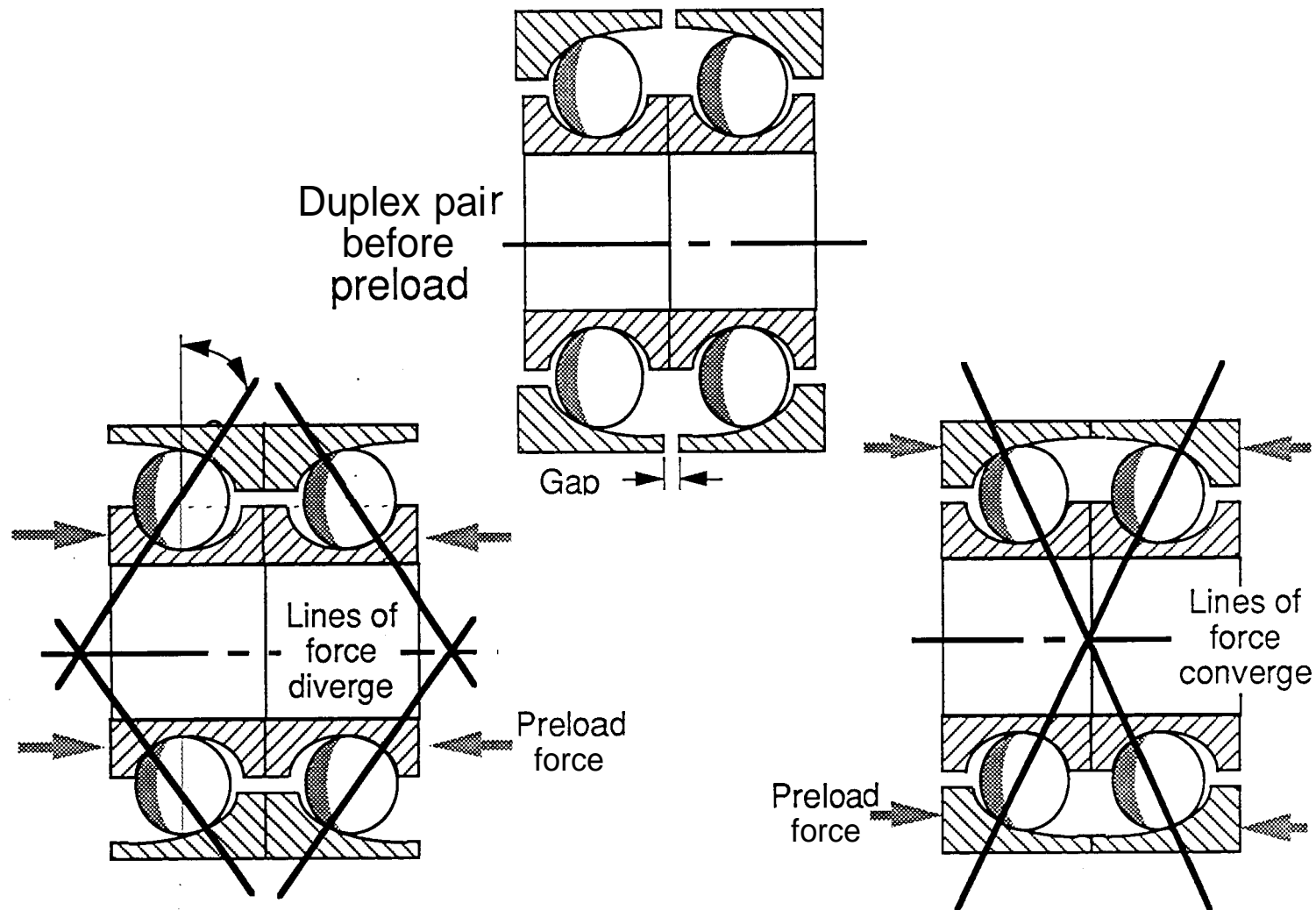
2. ACTUATOR COMPONENTS

Prime mover

Bearing

Sensor

Transmission

Signal transfer
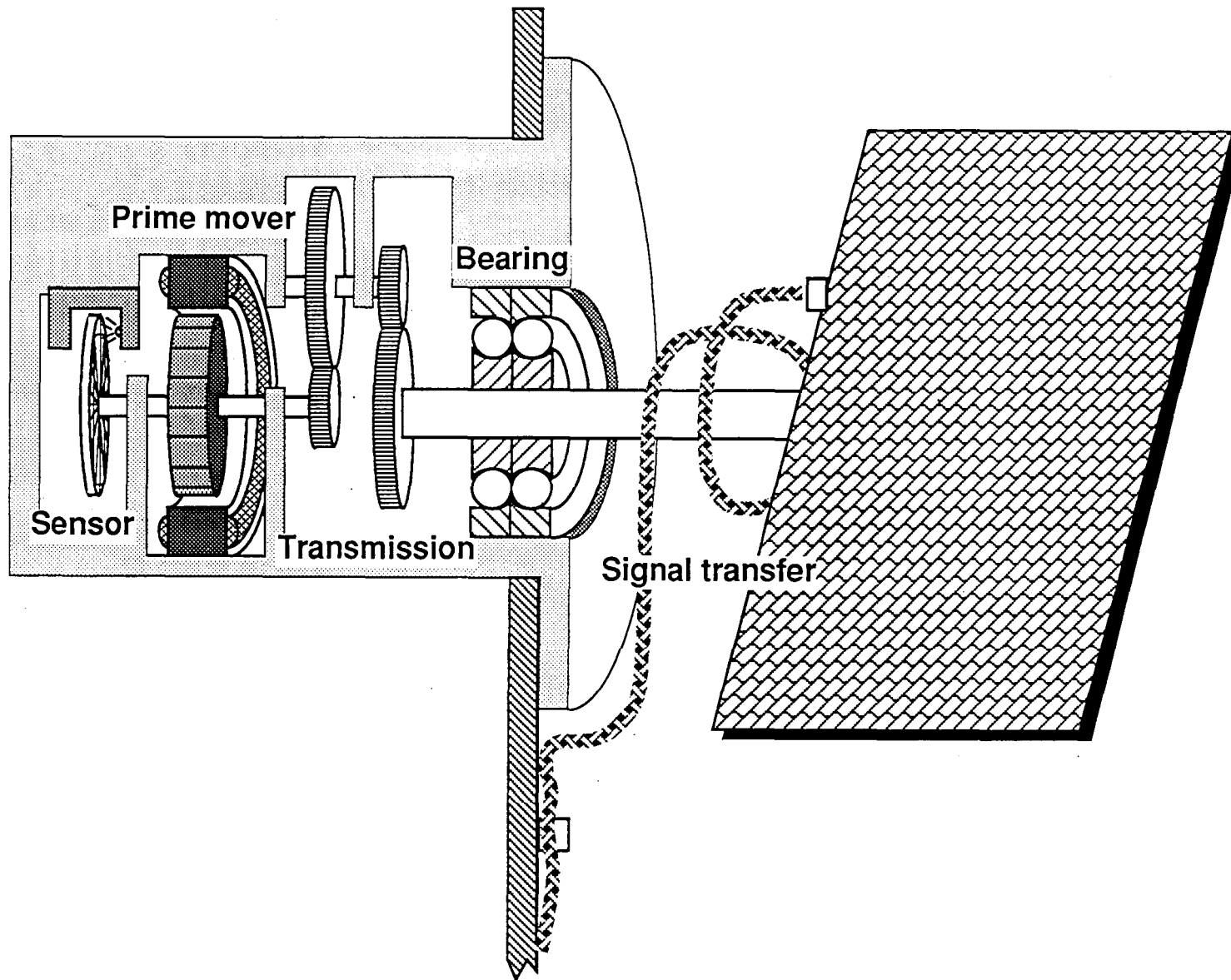
2.1 BEARINGS

- Devices which *predictably* constrain motion in some axes, allow motion in others.

- The best, most commonly used bearings for precision space applications are:
  - Angular-contact ball bearings
  - Flexures

- The most promising future bearing technology is:
  - Magnetic suspensions
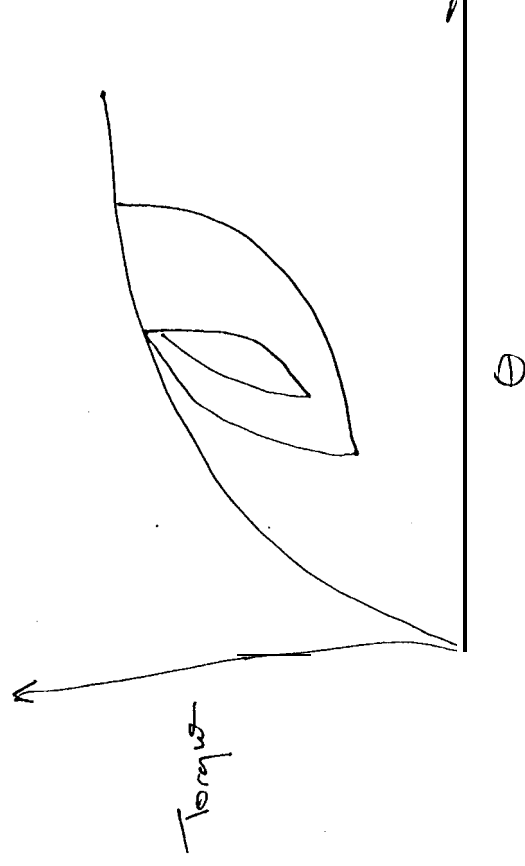
2.1.1 Angular Contact Ball Bearings

Duplex pair before preload

Gap

Lines of force diverge

Preload force

Lines of force converge

Preload force

Preloaded Back-to-Back, or DB
Resists cross-axis moment

Preloaded Face-to-Face, or DF
Does not resist cross-axis moment

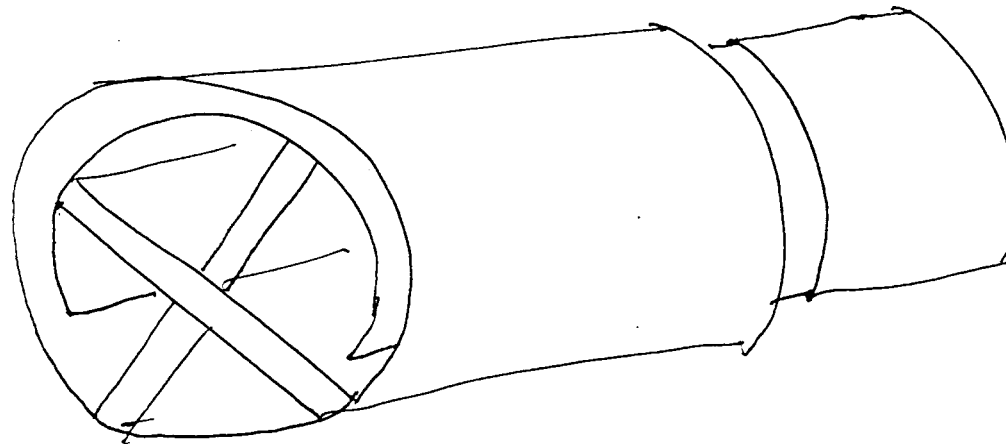# 2.1.1 Angular Contact Ball Bearings

insert drawing of Dahl Friction

Torque

θ

Equation ———
Rules of hysteresis loops: ———

2.1.2 Flexures

insert drawing

2.1 Bearing Comparison

|	Ball Bearing	Flexure	Magnetic Suspension
Range of motion	Continuous	<±10°	Continuous
Stiffness of constrained axes	Highest, predictable	Predictable	High but bandwidth-limited. predictable
Axis of rotation precision	Runout as small as 0.0001"	Moves with rotation	Equivalent to ball bearing
Friction, torsional stiffness	Dahl friction, difficult to predict	Predictable torsional stiffness, increases with load capability.	Virtually zero friction and torsional stiffness
Life	Prediction based on previous experience	Can be designed for infinite life	Limited by electronics only
Temperature range	Limited	Widest	Wide
Contamination	Lubricant must be contained	None	None
Availability	Wide variety of sizes, configurations	Generally requires custom design	No NASA flight heritage

2.2 Prime Movers

- Common prime movers for precision flight actuators:
    - DC brushless motor
    - Stepper motor
    - Voice coil
    - "Smart Materials" (piezoelectric, electrostrictive, etc.)

2.2.1 DC Brushless Motors
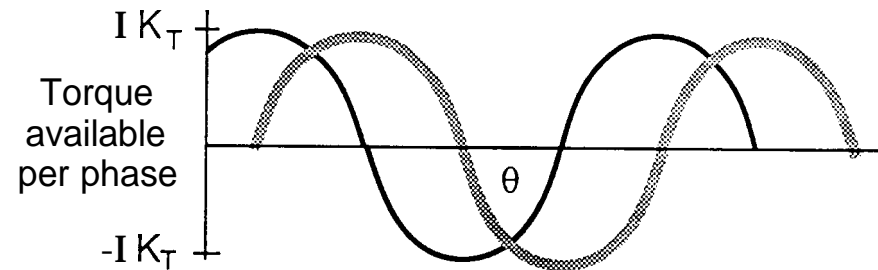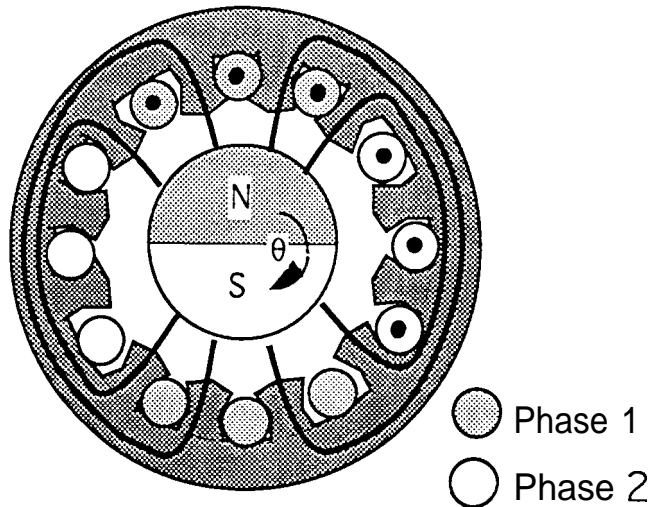
$$\tau_{total} \approx II\, K_T \cos(\theta) + I_2 K_T\ \sin(\theta)$$

Square-Wave Commutation
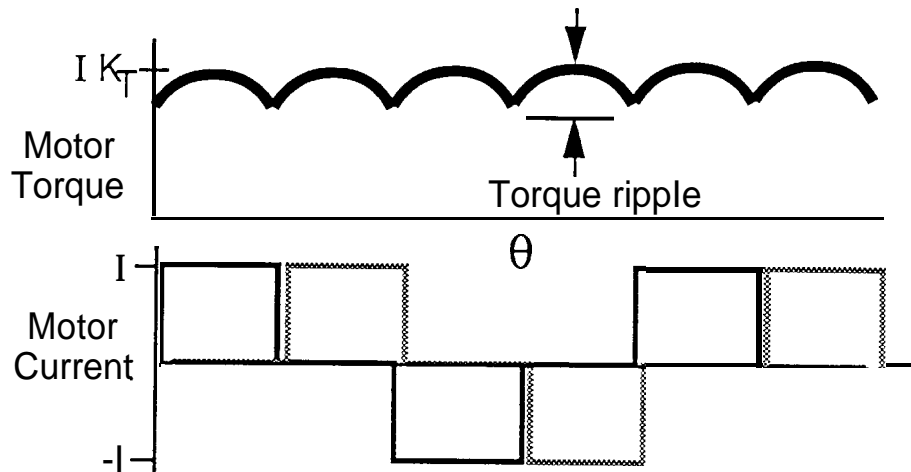
Low resolution angle knowledge required

Sinusoidal Commutation

$$1_1 = 1\,\cos(\theta),\ 1_2 = 1\,\sin(0)$$

$$\tau \approx I\, K_T$$

High resolution angle knowledge required, Torque ripple ≈ 0

2.2 Motor Comparison

	Brushless motor	Stepper motor
Motion increment	Continuous	1,6 rads to 26 mrads per mechanical step, 125 urad per microstep
Power efficiency	High	Low
Holding torque	Requires power	Passive detents at mechanical steps
Rate stability	Smooth	Inherently poor
Torque modelability	Easy to model	Difficult to model
Open-loop operation	No	Yes
Mechanical impedance	Low	High
Electronic Complexity	Complex	Simple

2.3 Displacement Sensors

Common displacement sensors for precision flight actuators:

- Resolver
- Inductosyn™
- Optical encoder
- Potentiometer
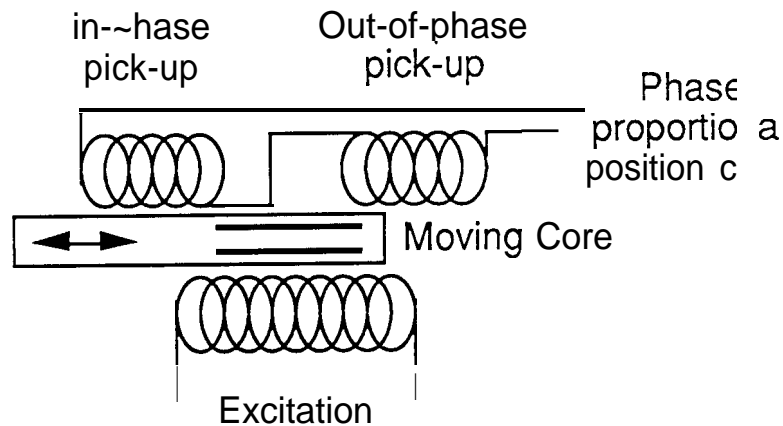- Linear (or Rotary)-Variable Differential Transformer (LVDT /RVDT)

2.3.1 Resolver, Inductosyn™, and LVDT

Excitation Coil
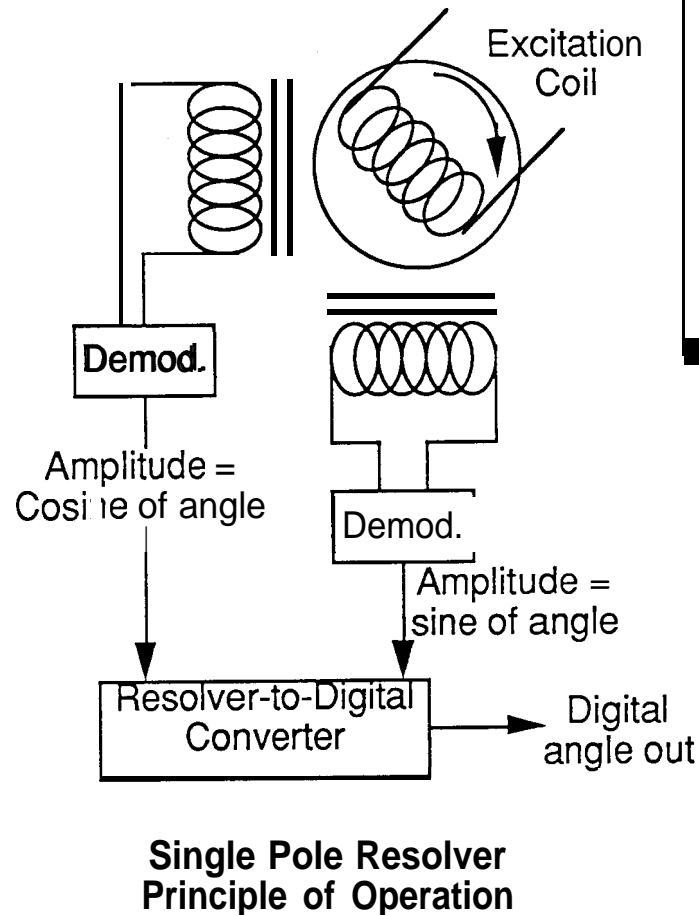
An **Inductosyn** is a multi-pole "pancake" resolver with printed windings.

.Up to 1024 poles/rev available.

•Absolute knowledge obtained with an additional single pole winding, or correlation between an N-pole and an N-1 pole winding.

Demod.

Amplitude =
Cosi₁e of angle

Demod.

Amplitude =
sine of angle

Resolver-to-Digital Converter

Digital angle out

in-~hase pick-up

Out-of-phase pick-up

Phasε proportio a position c

Moving Core

Excitation

Single Pole Resolver Principle of Operation
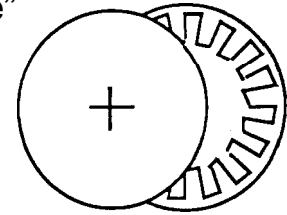
An **LVDT** is similar to a resolver, with a moving core and fixed windings

2.3 Sensor Comparison

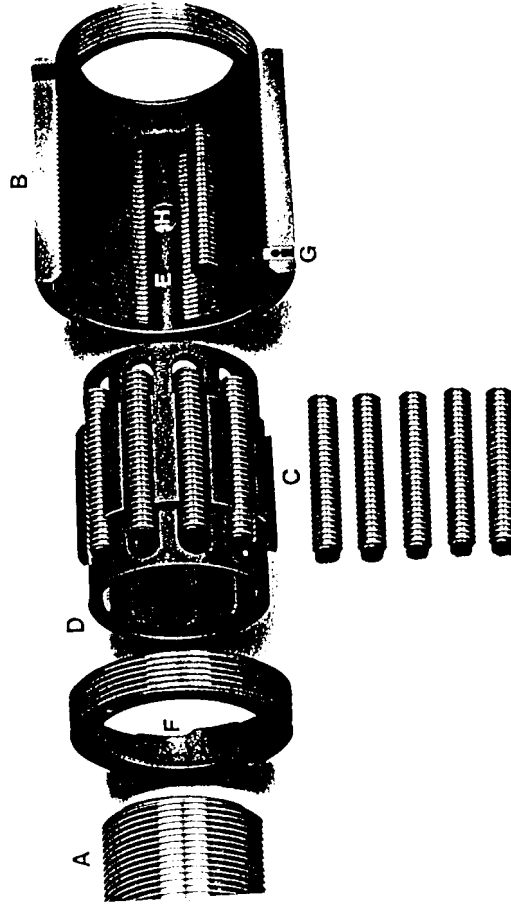|	Resolver	Inductosyn™	Encoder	Potentiometer
Accuracy	<100 µrad	< 1 µrad	25 µrad	10 mrad
Mass	Highest	Low	High	Lowest
Power	High	Highest	Low	Lowest
Integration with **motor**	Simplest	Requires tighter alignment than resolver	Separate assembly connected by flexible coupling	Separate assembly connected by flexible coupling
Reliability	High	High	Limited by LED	Subject to electrical noise and wear
Signal transfer	Requires rotary transformer or leads	Requires rotary transformer or leads	None	Requires brushes
output	Analog sine & cosine or digital word	Digital word	Digital word or quadrature pulses	Analog
Electronics complexity	Complex	Most complex	Simple	Simplest

2.4 Transmissions

- Common mechanical transmissions for precision flight actuators:
    - Spur gears
    - Planetary gears
    - Harmonic drive
    - Ball screw/roller screw
    - Band drive (rotary to linear, rotary to rotary)

2.4.1 Harmonic Drive

Flex Spline
(output)
with N-2 teeth

45" rotation of Wave
Generator

180° rotation
of Wave
Generator

Circle Spline
(fixed) with
N teeth

Wave
Generator
(input)

Flex Spline rotates 1
tooth in opposite direction
for 180° of Wave
Generator rotation

Gear Ratio = -N/2 :1

Characteristic Error

Frequency: Twice
per input revolution

Hundreds of
mrads

1 output
revolution
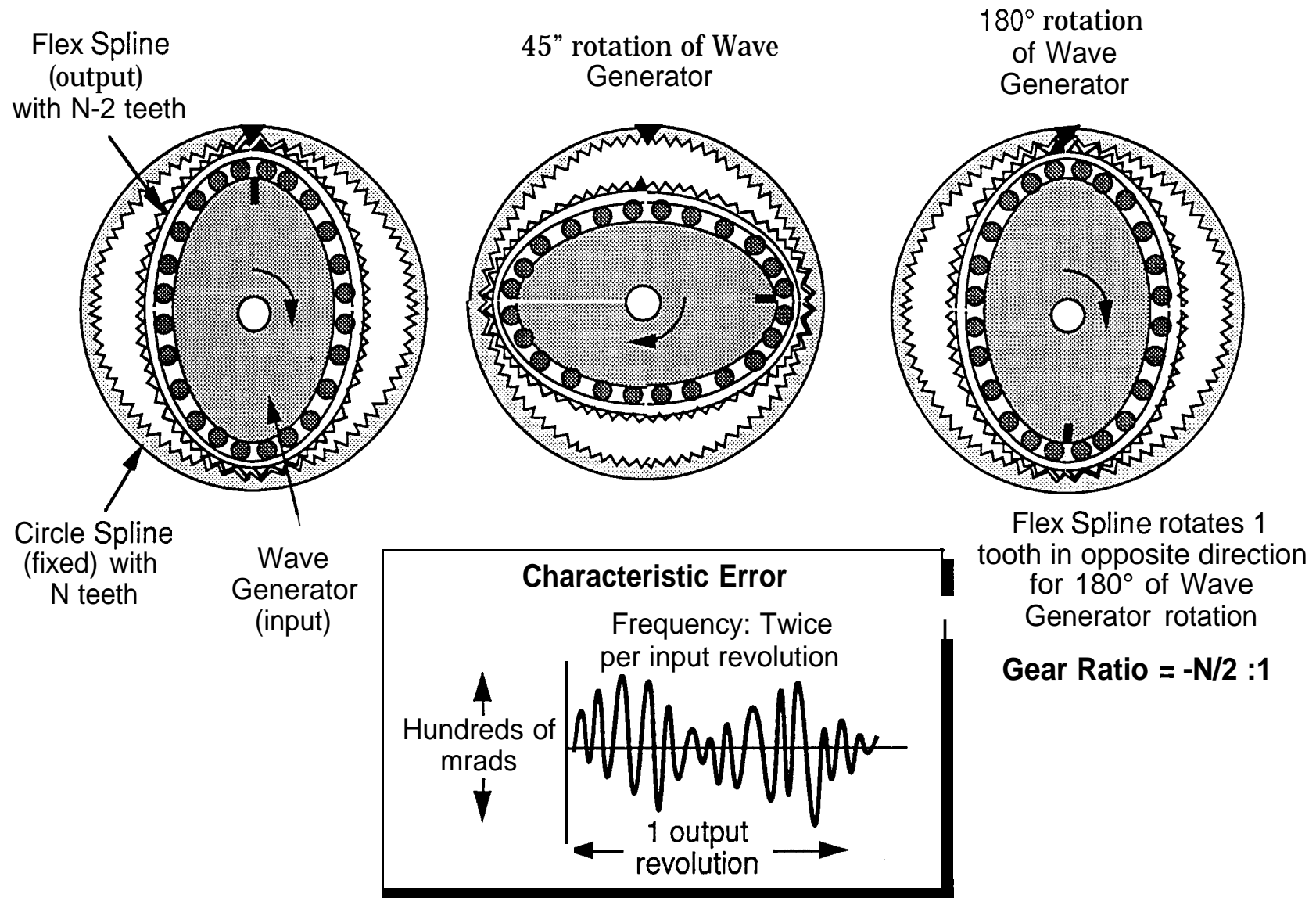
Actuator Components

2.4.2 Ball and Roller Screws
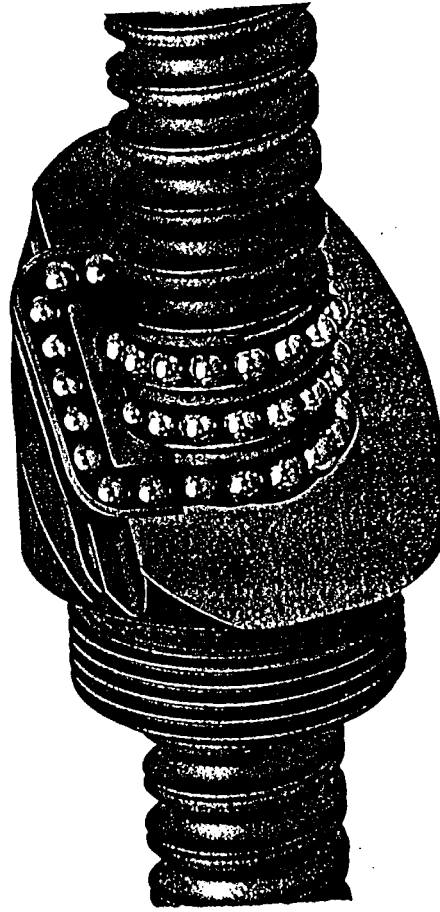
Figures courtesy of SKF

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Actuator Components

2.4.3 Band Drive

Actuator Components
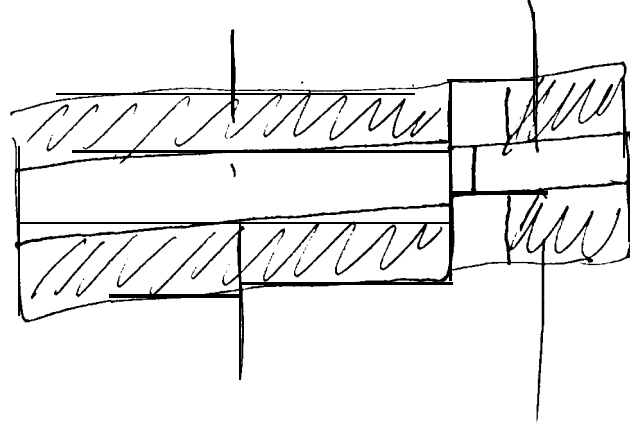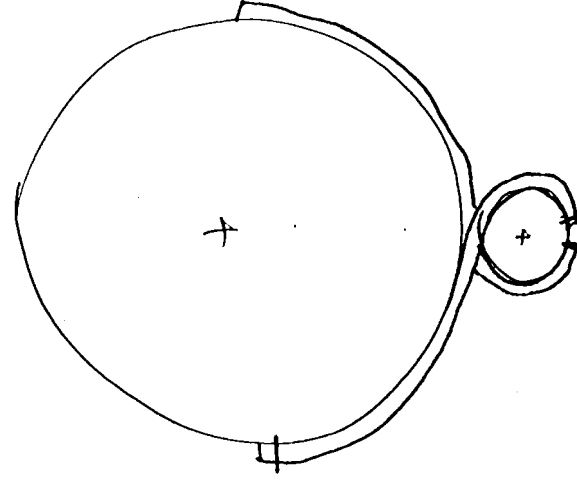
2.4 Comparison of Transmissions

	Gear train	Harmonic Drive	Ball/roller screw	Band drive
Mechanical Advantage	Nearly any ratio	60:1 to 200:1	up to 2 mm/rev for ball screw, up to 1 mm/rev for roller screw	Not much greater than 10:1
Lost motion	Anti-backlash gears available	Gear error	Thread error, Can be preloaded to eliminate backlash	Vitually none
Fr ct on	Depends on ratio, no. of Passes.	-0.05 Nm	Depends on preload	Extremely low
Life	Decreases with mechanical advantage	Slightly less than that of ball bearing	Comparable to that of ball bearings	Limited by bearings

Actuator Components

2.5 Signal Transfer

Signal Transfer Devices:

- Cable service loop
- Flex tape assembly
- Slip ring assembly
- Roll ring assembly
- Rotary transformer
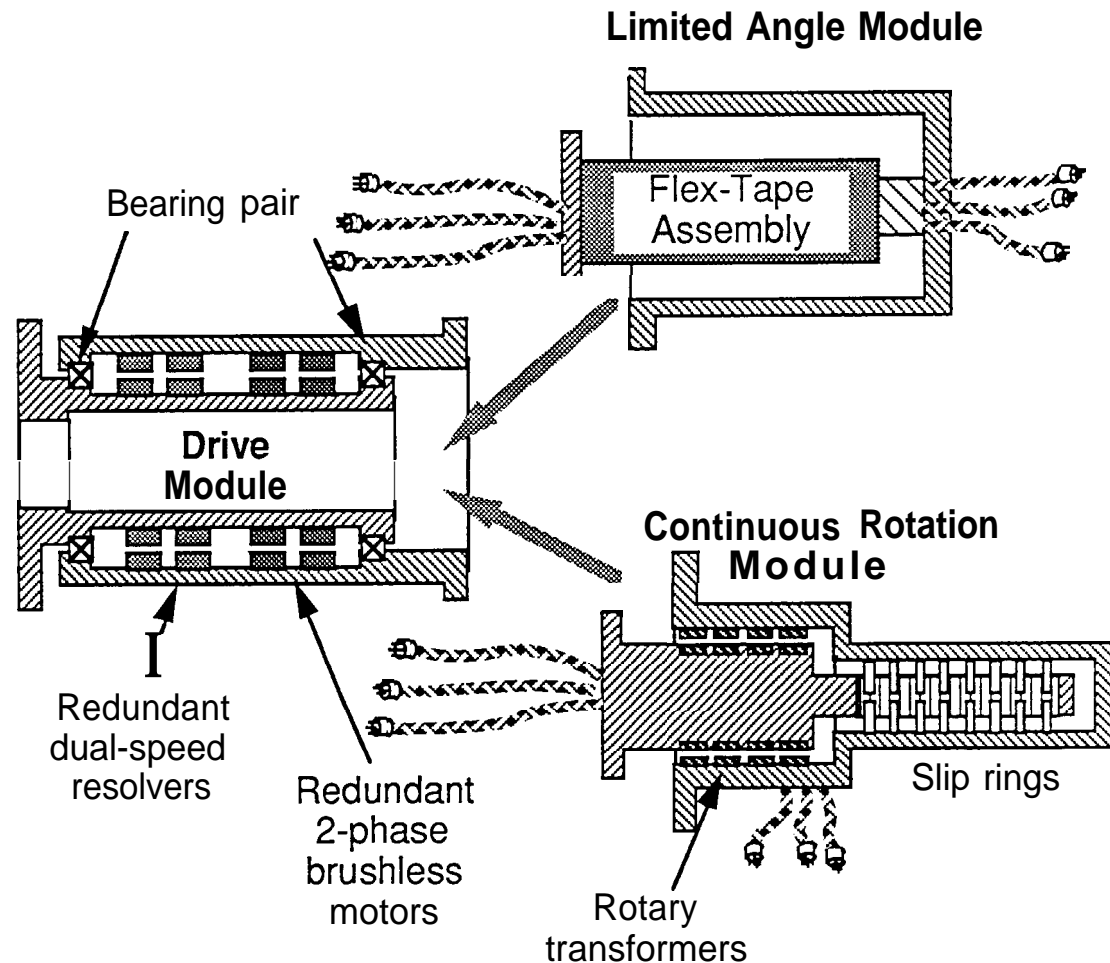
2.5 Signal Transfer Comparison

	Cable	Flex-tape	Slip rings	Rotary transformer
Range of motion	<180°	<360°	continuous	continuous
Mechanical impedance	Non-linear stiffness, hysteresis	Low non-linear stiffness, hysteresis	Coulomb friction	No mechanical contact
Life	Limited by fatigue	Limited by fatigue, >10^7 cycles	Limited by wear. >10^7 cycles	Unlimited
Signal compatibility	Unlimited	Unlimited	Best for low-bandwidth analog signals	Inefficient for power transfer. Limited to narrow frequency range
Reliability	Stiffness difficult to predict, can hang up.	High	Wear debris can cause shorts	High

3. Actuator Examples

- Direct drive
- Stepper/harmonic drive
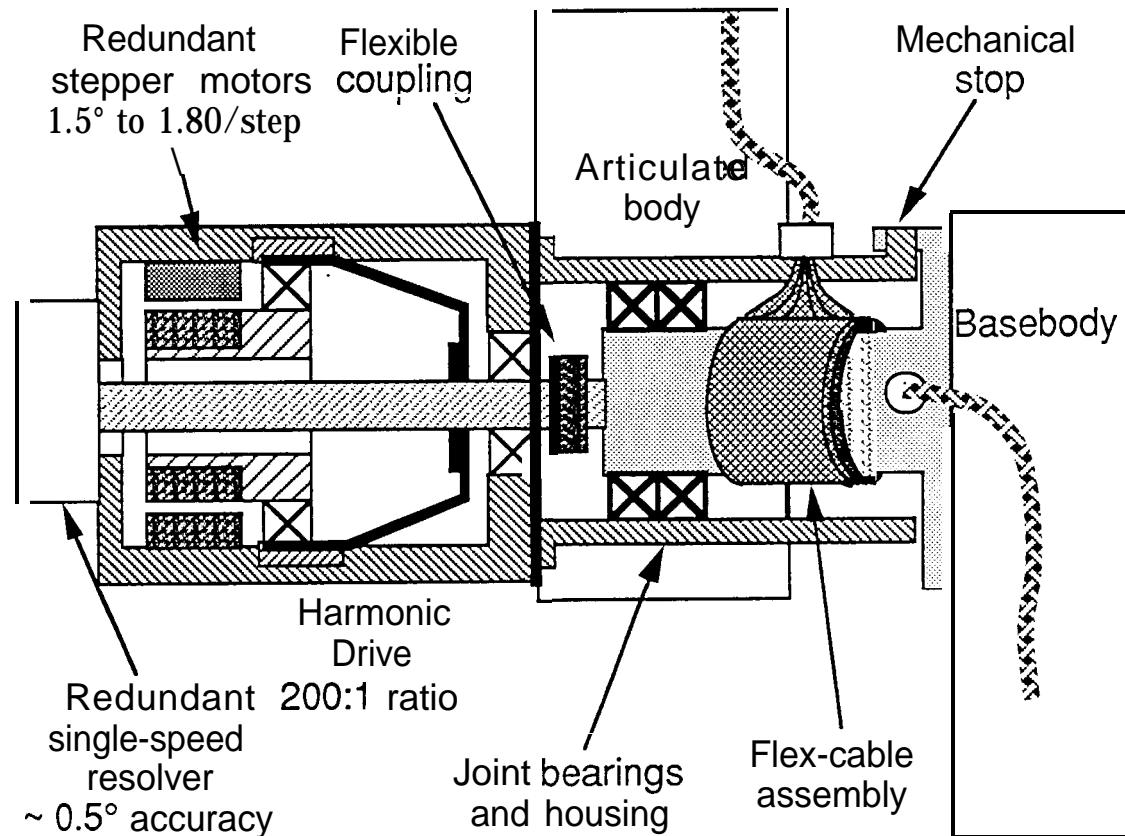- Motor/roller screw
- Linear motion band drive

3.1 Direct Drive

- **Low mechanical impedance ideal for disturbance isolation, inertial pointing.**

- **Used on Galileo (with encoder), proposed for Cassini scan platforms.**

- **Gyro on scan platform used for control, resolver used for commutation & spacecraft pointing**

- **Pointing stability: 10μrad over 0.5 sec at rate**

- **Cost: >$1 million**

Limited Angle Module

Flex-Tape Assembly

Bearing pair

Drive Module

Continuous Rotation Module

Redundant dual-speed resolvers

Redundant 2-phase brushless motors

Slip rings

Rotary transformers

3.2 Stepper motor with Harmonic Drive

- High mechanical impedance for body-relative pointing.

- Used for Magellan and TOPEX solar array drives. Proposed for POINTS solar array drive.

- Several standard sizes available from several vendors

- Output bearing is independent of actuator for ease of integration.

- Cost: << $1 million

Redundant stepper motors 1.5° to 1.80/step

Flexible coupling

Articulated body

Mechanical stop

Basebody

Harmonic Drive 200:1 ratio

Redundant single-speed resolver ~ 0.5° accuracy

Joint bearings and housing

Flex-cable assembly

3.3 Linear Actuator for POINTS Interferometer Articulation

- **High mechanical advantage for extreme accuracy.**

- **Passive holding force to withstand launch loads, flexure torsional stiffness.**

- **Reliability maximized by minimizing stages.**

- **Based on Viking & Cassini engine gimbal actuator.**

- **Range: ±3°**

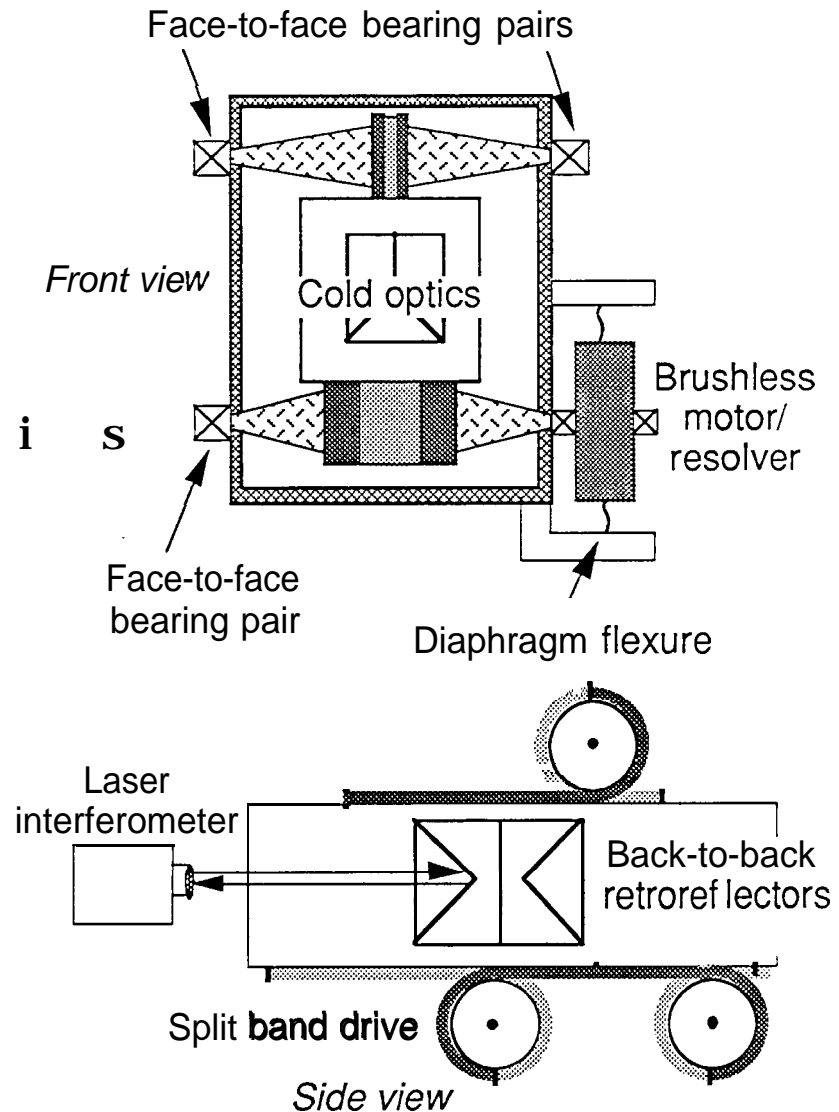- **Accuracy: 2.4 μrad with interferometer feedback**

- **Cost: <\$ 1 million**

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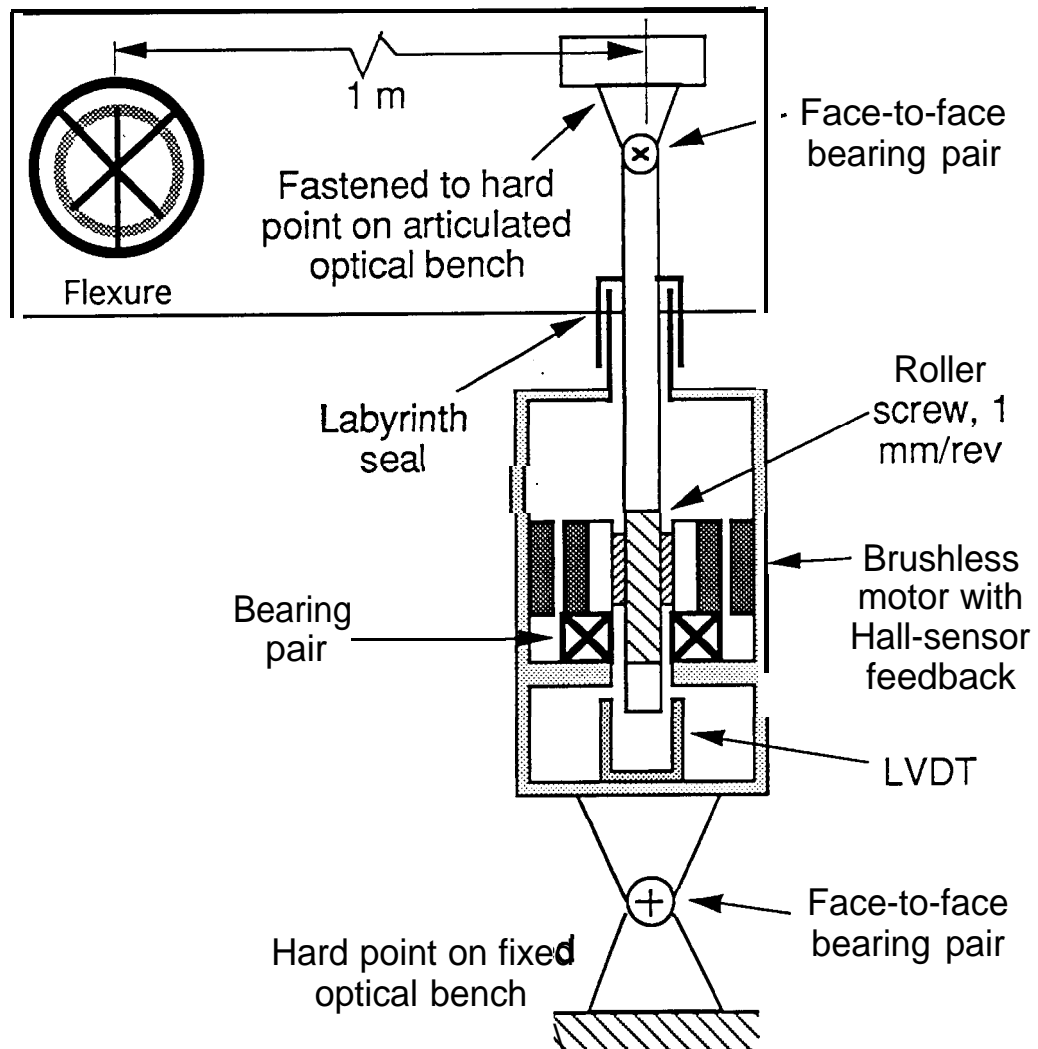
3.4 Linear Band Drive

Proposed for Tropospheric
Emission Spectrometer
delay line actuation.

Face-to-face bearing pairs

- Bearings and motor
thermally isolated from
-123 C optics.

Front view

Cold optics

Breadboard to be tested t   h   i   s
summer

Brushless
motor/
resolver

Face-to-face
bearing pair

- Requirements
  - ● Rage:17 cm+
    turn-around
  - ●Rate: 2 cm/s
  - ●Rate stability: ±5%
  - ●Life: 1 million cycles,

Diaphragm flexure

Laser
interferometer

Back-to-back
retroref lectors

- cost: > $1 million

Split **band drive**

Side view

4. Tips on Specifying Actuators

Rules of Thumb:
- Get actuator engineer involved early in the design phase.
- Try to accommodate devices, or at least major components with heritage.
- Don't specify a device with heritage unless you thoroughly understand its capabilities.
- Use components with predictable behavior; tests and analyses to prove compliance with requirements as major cost drivers.
- Keep is simple; complexity = cost.

Requirement Tips:

Position and rate performance
- Define terms precisely, and preferably with graphics.

Disturbance spectrum
- Requires integrated structural-optical model of spacecraft.

Launch loads
- Launch loads, not operating loads, size most mechanisms.
- Deployable structures are usually over-constrained when stowed, complicating loads analysis.
- Caging mechanisms are not trivial.

Resource allocation (mass, power, cost)
- Most mechanisms can trade mass for power.